INTEGRAL AND NUCLEAR ASTROPHYSICS

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We briefly review the fundamentals of nuclear gamma-ray line astronomy (radioactive astronomy), focusing on its role to decipher the intimate physics of supernovae, either immediatly (via ^{56}Co) or after a time delay (via ^{44}Ti). All kinds of supernovae can be in principle tested through their radioactivities and their associated gamma-ray lines. Dedicated to the spectroscopy and imaging of celestial sources in the 15 keV to 10 MeV band, the ESA scientific observatory INTEGRAL will open a golden age of nuclear astrophysics in Europe.

1 Why a new gamma-ray astronomy mission?

Gamma-ray astronomy explores the most energetic phenomena that occur in nature and addresses some of the most fundamental problems in astrophysics. It embraces a great variety of gamma-ray continuum and gamma-ray line production processes: nuclear excitation, radioactivity, positron annihilation and Compton scattering; and an even a greater diversity of astrophysical objects and phenomena: nucleosynthesis, nova and supernova explosions, the interstellar medium, cosmic-ray interactions and sources, neutron stars, black holes, gamma-ray bursts, active galactic nuclei and the cosmic gamma-ray background. Not only do gamma rays allow us to see deeper into these objects, but the bulk of the power radiated by them is often at gamma-ray energies.

In the low-energy gamma-ray band, line-forming processes such as nuclear excitation, radioactivity, positron annihilation, cyclotron emission and absorption become important, and when used as astrophysical tools. Unique astrophysical information is contained in the spectral shift, line width, and line profiles. Detailed studies of these processes require the resolving power of a germanium spectrometer. Lower-resolution spectrometers (e.g. SIGMA, OSSE, COMPTEL) did not have sufficient energy resolution to permit a study of the parameters of these lines. The last high-resolution space instrument, that on HEAO-3 in 1979-80, was 100 times less sensitive than required to tackle the scientific subjects outlined below. Solid observational and theoretical grounds already exist for predicting detectable line emission from such varied celestial objects as the Central region of the Galaxy, the interstellar medium, compact objects, novae and supernovae and a variety of active galactic nuclei.

2 Nuclear astrophysics and gamma-ray astronomy

2.1 Generalities

The observability of gamma-ray lines is conditionned by three factors:

a. Thermonuclear synthesis in stellar furnaces of fresh radioisotopes in significant abundance (N).

b. Quick removal (before decay) from the dense medium of birth to avoid burning and allow transfer to low density regions, transparent to gamma rays.

c. Lifetime sufficiently short (radioactive constant, λ, high enough) in order to get measurable activity (λN), i.e. enough photons to be detected at galactic/cosmic distances.

The list of candidates consequently is rather brief; it includes principally ^{56}Co, ^{44}Ti and ^{26}Al (the lifetimes are respectively 112 days, 87 years, 10^6 years).

The observation of nuclides through the gamma-ray lines emitted in the course of their natural decay in the circumstellar/interstellar media reveals the recent nucleosynthesis activities on time scales comensurate to their lifetime. According to the species involved, one can probe individual events, like supernovae and novae or collective effects of these objects at galactic scale. The two limiting cases are the following:

i) if the lifetime is short(^{56}Co) compared to the frequency of the relevant event (SN explosion in this case) one has the possibility of observing individual events.

ii) if the lifetime is long compared to the frequency of fertile events (^{26}Al) one should observe the collective effect of many events under the form of a diffuse galactic emission. For lifetimes of the order of the recurrence time (rate) , i.e. ^{22}Na and ^{44}Ti, the case is intermediate. One should then observe diffuse extended sources.

The line profiles offer a wealth of information on the detailed physics/ dynamics of the astrophysical sources of unstable isotopes [1 2]. Gamma ray lines are indeed ideal diagnostics of nucleosynthesis. Stringent constraints on stellar and supernova yields can be set by specific line intensity or even upper limits on these. Gamma-ray line astronomy, in principle should allow to test both quiescent (hydrostatic) nucleosynthesis (in AGB and Wolf- Rayet stars) and explosive nucleosynthesis (novae and supernovae). We focus here on supernovae (for the other objects see J. Knodlseder and M. Hernanz, this conference). We are concerned here by the high potential of these exploding objects in both the synthesis and acceleration of nuclei.

2.2 Gamma-ray lines and supernova physics

A highligt of gamma-ray line astronomy has been the observation of signatures of the radioactive decay (weak interaction) of $^{56,57}Co$ isotopes, implied in the $^{56,57}Ni$ chain ending at $^{56,57}Fe$ from the supernova SN1987A in the Large Magellanic Cloud. Radioactive decay proceeds, in all cases considered, through the weak interaction (β^+ decay or electron capture) transforming inside a nucleus a proton into neutron. Indeed the synthesized species, due to the physics involved, are too proton rich to be stable. This proton richness is itself related to the fact that most of the reactions that built complex nuclei are induced by protons and alphas. This is especially true for explosive nucleosynthesis in supernovae, where the symetrical ^{44}Ti (22 protons and 22 neutrons) and ^{56}Ni (28 protons, 28 neutrons) are formed by successive alpha captures on ^{28}Si.

All kinds of supernovae can be tested (Ia,b,c and II) both through their radioactivity and also their (collective) particle acceleration effect.

i) individual SNII: There is very little chance to capture the cobalt-iron gamma-ray line emission of a new core collapse supernova during the lifetime of the present generation of gamma-ray satellite. However young supernova remnants could show up through the ^{44}Ti lines and through superbubbles excavated in the interstellar medium by the combined effect of strong stellar winds of massive stars and explosions. Due to its lifetime, of the order of a century, ^{44}Ti is well suited to discover young SNR hidden in the galactic dust. ^{44}Ti decay lines from recent SNR (Cas A and Vela junior) without optical counterpart have already been detected. Thus we have at least two cases of hidden supernovae. How many others will the INTEGRAL mission discover? The estimates are rather uncertain [3]. The detailed exploration of the known sources, associated to X ray data from Chandra and XMM, should allow to derive the distribution of ^{44}Ti and its mass (taking into account the fact that its lifetime against electron capture is possibly modified by very high state of ionisation of the emitting regions), setting important constraints on the physics of the explosion.

ii) collective effects of SNII in Superbubbles: Non thermal nucleosynthesis of Lithium-Beryllium-Boron (see M. Cassé, this conference) could also be accompanied by specific (rather wide) gamma ray lines, specially those of C*, O* and the LiBe feature arising from the alpha + alpha reaction [4] [5].

Indeed, superbubbles seem to be the most favourable sites of production of non thermal gamma-ray lines.

iii) SNIa: A direct observation of the gamma ray lines associated to ^{56}Co from a SNIa (closer than 15 Mpc) would be a very happy event. It could serve to clarify the thorny physics of these objects, which serve, on the other hand, as distance indicators for cosmology.

3 The INTEGRAL mission

3.1 Overall presentation

Dedicated to the spectroscopy and imaging of celestial sources in the 15 keV to 10 MeV band, the ESA (European Space Agency) scientific mission INTEGRAL (International Gamma-Ray Astrophysics Laboratory) will address the scientific objectives defined above through the simultaneous use of two main gamma-ray instruments, the high resolution spectrometer SPI and the fine imaging telescope IBIS, with concurrent source monitoring in the X-ray and visible bands. High resolution spectroscopy with fine imaging and accurate positioning of celestial sources over the entire energy range are mandatory to reach the scientific goals of the mission. Fine spectroscopy over the entire energy range will permit spectral features to be uniquely identified and line profiles to be determined for physical studies of the source region. Fine imaging capability within a large field of view will permit the accurate location and hence identification of the gamma-ray emitting objects with counterpart at other wavelengths. It will also enable extended regions to be distinguished from point sources and provide considerable serendipitous science. Explicit references on INTEGRAL science can be found in the proceedings of past INTEGRAL Workshops held in les Diablerets [6], Saint Malo [7], Taormina [8], and Alicante [9].

The INTEGRAL spacecraft (Figure 1) consists of a service module, commonly designed with the service module of the ESA XMM-Newton mission containing all spacecraft subsystem and a payload module containing the scientific instruments. INTEGRAL, with a payload mass of approximatly 2000 kg and a total launch mass of about 4000 kg will be launched in April 2002 by a Russian PROTON launcher into a highly eccentric 72-hour orbit (initial perigee height 10 000 km, initial apogee height 153 000 km). The particle induced background affects the performance of high-energy detectors, and scientific observations will therefore be carried out while the spacecraft is above an altitude of nominally 40 000 km, implying that 90% of the time spent on the orbit can be used for scientific observations. However, when taking into account several in-orbit activities (as e.g. slew and instrument calibration), the average observation efficiency becomes about 85 % per year. The spacecraft employs fixed solar arrays: this means, that the target pointing of the spacecraft (at any point in time) will remain outside an avoidance cone around the sun and anti-sun. This leads to a minimum angle between any celestial source and the sun/anti-sun of 50 degrees during the nominal mission life.

INTEGRAL will be an observatory-type mission with a nominal lifetime of 2 years, an extension up to 5 years is technically possible. Most of the observing time (65% during year 1, 70 % year 2 and 75 % after) will be awarded to the scientific community at large as the General Program. Typical observations will last up two weeks. Proposals following a standard AO process, will be selected on their scientific merit only by a single Time Allocation Committee. The first call for observation proposals, released in November 2000, has been closed on February 16, 2001. The remaining fraction of the observing time will be reserved, as guaranteed time, for the INTEGRAL Science Working Team for its contribution to the program. This fraction, the Core Program, will be devoted a Galactic plane survey, a deep exposure of the central radian of the Galaxy and pointed observations of selected regions (such as the Vela region) and targets of opportunity (TOO). In accordance with ESA's policy on data rights, all scientific data will be made available to the scientific community at large one year after they have been released to the observer. For more information see the INTEGRAL World Wide Web pages[10].

The INTEGRAL Science Data Center (ISDC) located in Versoix, Switzerland, close to the Geneva Observatory, will be the center in which the INTEGRAL payload telemetry data will be processed to a level at which all users can pursue the scientific interpretation of the data. The data will be corrected for instrumental signature and some standard scientific processing and analysis will be performed. The ISDC is the place where the archive and derived products will be built and made accessible to the world wide astronomical community. The ISDC will routinely monitor the instrument science performance and conduct a quick-look science analysis. Most of the TOO showing up during the lifetime of INTEGRAL will be detected at the ISDC during the routine scrutiny of the data. Scientific data products obtained by standard analysis tools will be distributed to the observers and archived for later use by the science community.

3.2 The spectrometer SPI

One of the two main INTEGRAL instruments, the spectrometer SPI (Figure 1), has been designed to perform spectral analysis of localized and extended

Figure 1. (Left) The INTEGRAL spacecraft. The cylindrically shaped SPI is next to the larger rectangular payload module (PLM) structure housing the IBIS and JEM-X detectors inside. The top of the PLM carries the coded mask for IBIS (squared) and the two coded masks for the two JEM-X detectors. The OMC is located at the left top of the PLM. (Right) Schematic view of the spectrometer SPI.

regions with performances at 1 MeV such as an energy resolution $E/\Delta E \sim 500$ and a 3σ line sensitivity of 5 10^{-6} photons s^{-1} cm^{-2} (10^6 s exposure). The instrument features an array of 19 hexagonal high purity germanium detectors cooled by an active device to an operating temperature of 85 K. An hexagonal coded aperture mask is located 1.7 m above the detection plane in order to image large regions of the sky (fully coded field of view $\sim$ 16 degrees) with an angular resolution of 2 degrees. In order to reduce background radiation, the detector assembly is shielded by a veto system which extends around the bottom and side of the detector almost completely up to the coded mask. A plastic veto is provided below the mask to further reduce the 511 keV background. The spectrometer SPI is being developed under prime contractor responsibility of CNES (the French Space Agency) by a consortium of institutes in France (CESR Toulouse, CEA Saclay), Germany (MPE Garching), Italy (IFCTR Milano), Spain (U Valencia), Belgium (U Louvain), UK (U Birmingham), USA (UC San Diego, LBL Berkeley, NASA/GSFC Greenbelt). Principal Investigators are G. Vedrenne (CESR Toulouse), and V. Schoenfelder (MPE Garching).

4 Conclusion

With the launch in the near future of the INTEGRAL spacecraft, a golden age of nuclear astrophysics will open in Europe, at the point of convergence of nuclear physics and astrophysics. Time is ripe to join this effort, especially having in mind the fact that INTEGRAL is an observatory-type mission with most of the total observing time being awarded as the general program to the scientific community at large.

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